USAARL-TECH-IR--2020-012

UNITED STATES ARMY AEROMEDICAL RESEARCH LABORATORY

Human Response Effects to Whole-Body Vibration in Aviation: A Brief Review

Matthew T. Ballard, Adrienne M. Madison, & Valeta Carol Chancey

Notice

Qualified Requesters

Qualified requesters may obtain copies from the Defense Technical Information Center (DTIC), Fort Belvoir, Virginia 22060. Orders will be expedited if placed through the librarian or other person designated to request documents from DTIC.

Change of Address

Organizations receiving reports from the U.S. Army Aeromedical Research Laboratory on automatic mailing lists should confirm correct address when corresponding about laboratory reports.

Disposition

Destroy this document when it is no longer needed. Do not return it to the originator.

Disclaimer

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation. Citation of trade names in this report does not constitute an official Department of the Army endorsement or approval of the use of such commercial items.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*: 21-04-2020

2. REPORT TYPE: Interim Technical Report

3. DATES COVERED *(From - To)*:

4. TITLE AND SUBTITLE
Human Response Effects to Whole-Body Vibration in Aviation: A Brief Review

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
Ballard, Matthew T.; Madison, Adrienne M.; Chancey, Valeta Carol

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Aeromedical Research Laboratory
P.O. Box 620577
Fort Rucker, AL 36362-0577

8. PERFORMING ORGANIZATION REPORT NUMBER
USAARL-TECH-IR--2020-012

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Development Command
810 Schreider Street
Fort Detrick, MD 21702

10. SPONSOR/MONITOR'S ACRONYM(S)
USAMRDC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Consult the attached references for more detailed information on the effects of whole-body vibration.

14. ABSTRACT
This document serves as a brief summary of the current state of knowledge regarding the biomechanical and physiological effects of whole-body vibration (WBV) exposure. While extensive research has shown the link between long-term WBV exposure and spinal disorders, little is known about the dose-response relationship from specific frequencies. Historically it has been recommended to avoid or minimize exposure to frequencies that overlap with resonance of the human body or its components, but many rotary-wing aircraft operate in these same ranges. More research is needed to understand the effects of these vibrations on acute and chronic injury risk and to build the dose-response relationship. This document provides an overview of effects deemed by the authors to be most relevant to aviator WBV exposure and the direction of current and proposed research from the U.S. Army Aeromedical Research Laboratory.

15. SUBJECT TERMS
WBV, whole-body vibration, human response, exposure, aviation, frequency, resonance

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLAS	UNCLAS	UNCLAS	SAR	18	Loraine St. Onge, PhD
					19b. TELEPHONE NUMBER *(Include area code)* 334-255-6906

This page is intentionally blank.

Table of Contents

List of Figures and Tables

List of Equations

This page is intentionally blank.

Relevance of Whole-Body Vibration Exposure

Evidence exists that long-term exposure to whole-body vibration (WBV) adversely affects a variety of human biomechanical and physiologic responses, ranging from motion sickness to physical disorders and fatigue. One of the most recognized health effects is the acceleration of the onset of spine disorders and fatigue, particularly of the lumbar region. WBV has been reported to adversely affect the gastrointestinal and cardiovascular systems, while WBV with repeated jolts (or multiple shocks of a higher magnitude that randomly occur during WBV) experienced by military personnel has been reported to potentially cause hematuria.

Spine-associated symptomology and pathology have been a well-recognized health concern for military aviators and aircrew in both fixed- and rotary-wing platforms for over 50 years. In military and civilian populations, lengthy periods of sitting (for more than half of a workday) in combination with WBV and/or awkward postures are significant factors associated with low back pain, intervertebral disk disease, spinal discomfort, and spinal disorders. Transient (acute) back pain in aviators is strongly related to average flight hours per day, while chronic back pain is more closely linked to total flight hours or cumulative vibration dose (Bongers et al., 1990). Extensive research has been conducted on vibration exposure with ground equipment workers. While a different setting than aviation, information from these sources can still be relevant due to the overlap in exposed frequencies between the applications. WBV exposure combined with lifting, frequent bending, twisted posture, and noise further associate with neck and shoulder/arm musculoskeletal disorders (Charles, Ma, Burchfiel, & Dong, 2018). In seated postures, when the cervical spine is in a fixed position, the cervical muscles are under constant, static work resulting in a powerful force that pulls on vertebral spinous processes in the lower cervical spine. This force combined with increased loading from WBV exposure has been linked with avulsion fractures of these spinous processes (Dupuis & Zerlett, 1987).

Aviators and aircrew are continuously and consistently exposed to all of these conditions in their operational environments. Symptoms may be localized, radicular, and referred and may include leg, buttocks, and back pain with numbness and muscle spasms. Complications resulting from the combination of these conditions can decrease concentration and situational awareness, impacting overall mission performance.

Whole-Body Vibration Standards

General guidelines for measuring and quantifying human exposure to WBV have been presented in both international (ISO-2631, 1997) and military (MIL-STD-810G, 2008; MIL-STD-1472G, 2012) standards; however, these standards do not set simple vibration duration exposure limits. ISO 2631 provides guidance on WBV measurement and analysis. According to ISO 2631-1, vibration frequencies obtained from different locations (e.g., seatback) and in different directions (i.e., x-, y-, or z-direction) are assigned different weightings depending on the purpose of analysis (e.g., health, comfort, perception, or motion sickness). Different weightings are used because the transmissibility of vibration through the body, and the resultant effect on the individual, can change with different inputs. For example, humans are at risk of motion sickness when exposed to vertical vibrations below 0.5 Hertz (Hz); therefore, when examining WBV effects on motion sickness, a higher amplitude weighting is given to frequencies below 0.5 Hz.

Similarly, most research has indicated the torso approaches primary resonance in the range of 5-6 Hz. This is reflected in the ISO 2631-1 weighting curves as higher weightings are given to frequencies in the 4-8 Hz range, when that measurement is acquired from the seat surface and occurs in the z-direction. ISO 2631-1 provides higher weightings for frequency ranges that include resonant frequencies of the human body. ISO 2631-1 does not provide information on the physiological or biomechanical effects that could be expected from specific frequencies. This is likely because such information did not exist in the current literature, or was not readily available at the time of writing for ISO 2631. There is research that displays a correlation between long-term exposure to vibration in these ranges and some musculoskeletal disorders, which is why the standard states to limit exposure in these frequency ranges. ISO 2631 information on classifying the risk of an adverse health effect in Part 1, Annex B and in Part 5, but the guidance offered is vague. The standard documents a health guidance caution zone (ISO 2631-1, Annex B) and classifications for low, moderate, and high probability of an adverse health effect at lifetime exposure (ISO 2631-5, 2001), but cautions against designating an amount of exposure as safe. Annex B states, “There are not sufficient data to show a quantitative relationship between vibration exposure and risk of health effects. Hence, it is not possible to assess whole-body vibration in terms of the probability of risk at various exposure magnitudes and durations.”

Rotary-wing aircraft have distinct equipment and WBV signature patterns, including major frequency content. MIL-STD-1472G states WBV shall be minimized in frequencies below 70 Hz. Major body resonances occur below 20 Hz and, while frequencies above 20 Hz have diminishing effects on the musculoskeletal system, ranges between 20 and 70 Hz can cause impairment of visual tasks. Fundamental frequencies generated by military rotary-wing aircraft fall within this lower range, with blade pass and harmonic frequencies reaching the higher ranges. MIL-STD-810G indicates the main rotor as the primary source of vibration experienced by occupants (Figure 1) and provides information on the frequencies measured in military aircraft (Table 1). MIL-STD-810G provides the aircraft fundamental frequencies and the formulas needed to calculate the blade pass (Equation 1), 1st harmonic (Equation 2), and 2nd harmonic (Equation 3) frequencies.

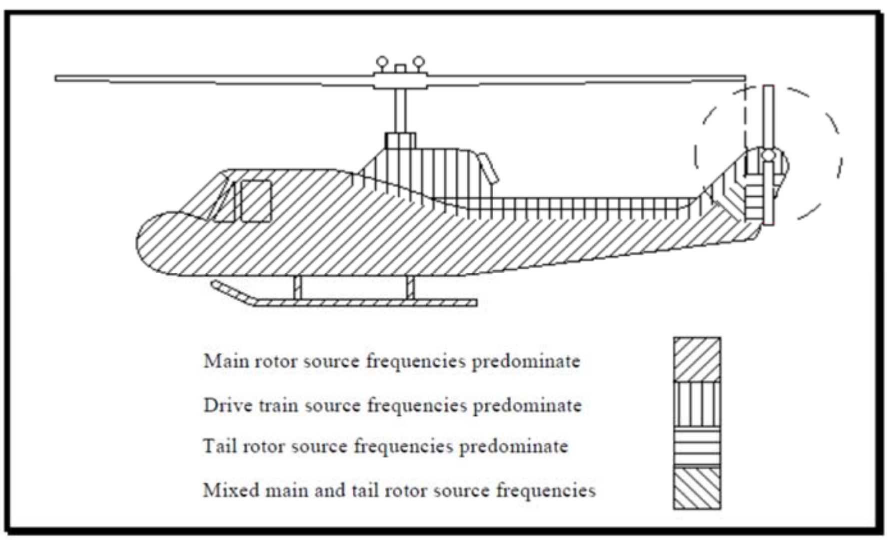

Figure 1: Helicopter Vibration Zones. Adapted from MIL-STD-810G.

Table 1: Rotary Wing Aircraft Frequencies. Obtained with data from MIL-STD-810G.

Aircraft	**Frequencies (Hz)**			
	Fundamental	**Blade Pass**	**1st Harmonic**	**2nd Harmonic**
AH-1	5.40	10.80	21.60	32.40
AH-6J	7.95	39.75	79.50	119.25
AH-6M	7.92	47.52	95.04	142.56
AH-64	4.86	19.44	38.88	58.32
CH-47D	3.75	11.25	22.50	33.75
MH-6H	7.80	39.00	78.00	117.00
OH-6A	8.10	32.40	64.80	97.20
OH-58AC	5.90	11.80	23.60	35.40
OH-58D	6.60	26.40	52.80	79.20
UH-1	5.40	10.80	21.60	32.40
UH-60	4.30	17.20	34.40	51.60

$$f_2 = n\ x\ f_1 \tag{1}$$

$$f_3 = 2\ x\ n\ x\ f_1 \tag{2}$$

$$f_4 = 3\ x\ n\ x\ f_1 \tag{3}$$

Where f_1 is the fundamental frequency; f_2 is the blade pass frequency; f_3 is the 1st harmonic frequency; f_4 is the 2nd harmonic frequency; and n is the number of main rotor blades.

In addition to frequency, MIL-STD-1472G also provides recommendations on acceleration limits. Similar to ISO 2631, vibration ranges that have displayed a correlation with health risks are to be minimized, but further information regarding the types of injury or decrement to be expected from specific zones is not available. Vibrations are to be assessed using ISO 2631-1 guidelines, with principal areas for measurement being the supporting seat surface, seatback, and feet. In practice, vibration measurements are typically acquired using tri-axial accelerometers placed at these positions, and vibrations are evaluated using the weighted root-mean-square (R.M.S.) acceleration. Per ISO 2631-1, the weighted R.M.S. acceleration can be calculated using the following equation (4) or with frequency-domain equivalents:

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}} \tag{4}$$

Where $a_w(t)$ is the weighted acceleration (translational or rotational) as a function of time (time history), in meters per second squared (m/s^2) or radians per second squared (rad/s^2), respectively; and T is the duration of the measurement, in seconds.

Past and Present Research

Dupuis and Zerlett (Dupuis & Zerlett, 1986) compiled an extensive summary of previous WBV research, including effects on physiological functions. A recently published review (Rakheja, Dewangan, Dong, & Marcotte, 2020) examines some of the effects described here along with providing a more detailed look into the biomechanical responses from WBV exposures in different operating environments (e.g., automotive, standing). Across different frequency ranges up to 20 Hz, individuals have experienced symptoms such as headaches, speech disturbances, respiration complaints, abdominal pain, and more. Individuals have expressed a constant urge to urinate and defecate while exposed to frequencies between 10 to 18 Hz (Dupuis & Zerlett, 1986). Colon pressure was found to pass 200% of resting measurements when an individual was exposed to frequency in the range of 4-5 Hz (White, Lange, & Coermann, 1962). Eyes approach resonance in the range of 20-25 Hz and visual acuity has shown to decrease when individuals are subjected to WBV (Dupuis & Zerlett, 1986). Resonant frequencies of the internal organs tend to fall in the same range of the torso resonant frequency, 4-5 Hz, and long-term exposure to these frequencies has been linked with associated disorders in some cases (Dupuis & Zerlett, 1986). Information on the correlation between WBV exposure and changes in heart rate are unclear. An increase in heart rate has been documented under extreme accelerations, but it is possible that the heart rate changes were due to other factors (e.g., faster movements, psychological) rather than as a result of vibration (Dupuis & Zerlett, 1986). Changes in respiratory rate have been found with a trend towards hyperventilation between 2 and 6 Hz, which is thought to occur from passive movement of the diaphragm and abdominal wall as a result of the vibration (Dupuis & Zerlett, 1986). Table 2 provides a summary of some known effects of WBV. Further effects on biochemical reactions (e.g., electrical characteristics of the skin, digestive processes, blood content, etc.) have been investigated; however, there is not a definitive link between these effects and disorder or injury.

This space is intentionally blank.

Table 2: Examples of Known WBV Effects

Vibration Frequency	Effect	Reference
< 1 Hz	Motion Sickness	ISO 2631-1, 1997; Dupuis & Zerlett, 1986
2 – 6 Hz	Hyperventilation	Dupuis & Zerlett, 1986
~4 – 10 Hz	Resonant frequency of the torso, peak transmissibility to the head; increased colon pressure; respiration complaints; abdominal pain; increased torque in spinal support muscles; jaw resonance; chest pain; general discomfort	Dupuis & Zerlett, 1986; White et al., 1963; Magid & Coermann, 1960; White et al., 1963; Seroussi et al., 1986
10 – 18 Hz	Urge to urinate and defecate	Dupuis & Zerlett, 1986
13 – 20 Hz	Headache; speech disturbances; increased muscle tension	Dupuis & Zerlett, 1986; Magid & Coermann, 1960
20 – 25 Hz	Decreased visual acuity	Dupuis & Zerlett, 1986

Note: Most legacy rotary-wing platforms have their fundamental frequency below 10 Hz.

Individuals exposed to WBV over long periods of time have been associated with increased occurrences of neck and back pain and musculoskeletal disorders (Bongers et al., 1990; Charles et al., 2018; Dupuis & Zerlett, 1987; Griffin, 2004; Kittusamy & Buchholz, 2004). A recent study found over 95% of surveyed aircrew personnel riding in the gunner seats of MH-60S complained of back pain, and all of the 18 flights measured were found to have vibration dose values above what is recommended in ISO 2631 (Blackman, 2019). Research examining causality between specific frequency ranges and injury is not readily available, but there has been work to document the response of the musculoskeletal system to WBV. Changes in muscle activation under vibration have been observed. For example, maximum paraspinal (spinal support) muscle contractions occur prior to maximum head acceleration at 2.5 Hz, but well after maximum head acceleration at 5 Hz (Seidel, 1988). The effect on muscle timing could impact the ability of an individual to brace or compensate for movements. Compared with static sitting, the estimated torque of paraspinal muscles significantly increases when the individual is exposed to vibrations in the range of 5 to 9 Hz (Seroussi, Wilder, & Pope, 1989). Greater muscle forces result in increased loading on the spine, which could place the individual under a higher risk of injury. The human spinal system has been found to exhibit characteristic responses to WBV inputs in a seated posture, with the primary resonance occurring between 4 to 7 Hz and subsequent resonances occurring in the range of 10 to

15 Hz (Dupuis & Zerlett, 1986; Malcolm H. Pope, Magnusson, & Wilder, 1998). Additionally, vibration transmissibility to the head peaks at approximately 4-5 Hz while sitting (Dupuis & Zerlett, 1986). Exposure to resonant frequencies and higher transmissibility causes larger displacements through the body, which results in more work from the muscular system to compensate. This may cause fatigue to increase at a higher rate, but research on fatigue has produced mixed results with some finding accelerated fatigue under WBV (Hansson, Magnusson, & Broman, 1991; Magnusson, Hansson, & Broman, 1988) and others finding no significant change in fatigue rate (M. H. Pope, Wilder, & Donnermeyer, 1986).

Aviators could be susceptible to these symptoms and others due to the frequencies produced by the aircraft. While the impact may not be direct, a performance effect should not be unexpected. Aviation-based vibration research at USAARL has primarily focused on measuring and understanding WBV signature patterns, investigating various WBV effects of aircraft and military vehicle platforms and equipment in transmitting mechanical WBV to military personnel (aircrew and patients) and assessing human biomechanical and/or physiologic response. Such work includes studies of seats and seat cushions (Butler & Alem, 1994) and patient immobilization systems (Kinsler, Khouri, Squire, Conti, & Wurzbach, 2018), as well as helmet and helmet systems (coined head-supported mass) (Alem, Meyer, & Albana, 1995; Barazanji & Alem, 2000; Barazanji et al., 1998; Butler, 1992; Butler & Alem, 1997) related to the health and performance of helicopter crew under WBV. Most research focused on WBV exposure in the vertical direction, as the body exhibits comparatively smaller responses when vibration is applied horizontally. While transmissibility was found to be less under horizontal vibration, Baig et al. (Baig et al., 2014) found the activation of spinal muscles in the lumbar and thoracic regions to be similar regardless of the direction (i.e., horizontal vs. vertical) of applied vibration. Vertical vibration is still considered to be more critical, but the finding on muscle responses complements previous studies, which found the lower back to play a key role in transmissibility (Dupuis & Zerlett, 1986) and have linked long-term WBV exposure to increased occurrences of back pain (Griffin, 2004; Kittusamy & Buchholz, 2004). Ongoing research at the U.S. Army Aeromedical Research Laboratory (USAARL) is using a WBV profile with volunteers seated in a rigid seat with fixed geometry and horizontal seat pan to reevaluate the previously developed USAARL aviation-based head-supported mass (HSM) performance curve. Specifically, USAARL is assessing user tolerance (i.e., sex differences and exposure duration risk) to currently- and future- fielded HSM configurations, with an additional focus on the resultant effects to the cervical spine.

Knowledge Gaps

Knowledge gaps remain in human and WBV dose-response relationships as they relate to physiologic, biomechanical, performance, and fatigue effects in aviation-unique environments. There is an abundance of publications that correlate WBV exposure with symptoms such as back pain, but information on causation is scarce. The level of vibration that initiates a decrease in aviator performance is not known. The current state of information only allows for an estimation of performance effects due to expected symptoms as a result of WBV exposure. Increased WBV exposure is linked with increased occurrences of spinal disorders; however, specific information on associations between frequency ranges and injury is lacking. Griffin (Griffin, 2004) stated, "there is no substantial body of knowledge showing what type of injury, the probability of injury, or the severity of injury that occurs with any duration of exposure to whole-body vibration."

While injury information is minimal, some information exists on physiological responses to WBV. As mentioned above, changes in muscle activation timing or force output under vibration have been documented. The frequencies where these effects are observed often overlap with resonant frequencies of the body or its components. Exposing an individual to these frequency ranges could place them at an increased risk of injury, as it hinders the ability of the body to compensate for these vibrations. The combination of these effects also leads one to the assumption that WBV will cause an increase in the rate of fatigue, but such effects have not been clearly observed or reported. Additionally, differences in seated postures in combination with WBV exposure can have different effects on injury risk. Given that rotary-wing aircraft aviators are subjected to these conditions, further investigation is needed to fully understand the biomechanical and physiological effects of these exposures and how the addition of other variables (e.g., head-supported mass, seat tilt) can change these effects.

Future Work

While it is known that long-term WBV exposure in frequency ranges that include operating frequencies of military rotary-wing aircraft is linked with musculoskeletal injury disorder, detailed information on how specific frequencies result in physiological or performance detriments is still unknown. More information on the relationship between WBV exposure and variables such as cognitive performance or spinal loading could provide further guidance on which vibrations to avoid or how to mitigate them. Using our experience, capabilities, and working relationship, we are proposing future aviation-specific WBV research to address two specific and relevant aims.

The first is to expand the state of knowledge of human and WBV dose-response as it relates to physiological, biomechanical, performance, and fatigue effects in dynamic aviation environments. The second aim is to investigate the biomechanical and physiological impact of seat recline on the head/neck complex and spine under HSM loading conditions during dynamic aviation environments by assessing changes in performance, neck strength, range of motion, pain, fatigue, and kinematics. Outcomes from the investigation of human WBV dose-response behavior relationships can be applied to the development of helmet and seating systems for emerging Future Vertical Lift (FVL) multi-domain operations and capabilities. This work will provide valuable support to legacy platforms and FVL cross-functional team and community needs.

This page is intentionally blank.

References

Alem, N. M., Meyer, M. D., & Albana, J. P. (1995). Effects of Head Supported Devices on Pilot Performance During Simulated Helicopter Rides. *USAARL Report, No. 95-37*.

Baig, H. A., Dorman, D. B., Bulka, B. A., Shivers, B. L., Chancey, V. C., & Winkelstein, B. A. (2014). Characterization of the Frequency and Muscle Responses of the Lumbar and Thoracic Spines of Seated Volunteers During Sinusoidal Whole Body Vibration. *Journal of Biomechanical Engineering, 136*(10). doi:10.1115/1.4027998

Barazanji, K. W., & Alem, N. M. (2000). Effects of Head-Supported Devices on Female Aviators During Simulated Helicopter Rides Part I: Biomechanical Response. *USAARL Report, No. 2000-16*.

Barazanji, K. W., Alem, N. M., Dodson, J., Erickson, B., Guerrero, R., & Reyes, S. (1998). Effects of Head-Supported Devices on Female Aviators During Simulated Helicopter Rides. *RTO, MP-19*.

Blackman, C. G. (2019). *Whole Body Vibration of Military Aircrews on MH-60 Seahawk Helicopters: Risk Assessment in Relation to Lower Back Pain.* Doctoral dissertation, UCLA.

Bongers, P. M., Hulshof, C. T. J., DlJkstra, L., Boshuizen, H. C., Groenhout, H. J. M., & Valken, E. (1990). Back pain and exposure to whole body vibration in helicopter pilots. *Ergonomics, 33*(8), 1007-1026. doi:10.1080/00140139008925309

Butler, B. P. (1992). *Helmeted Head and Neck Dynamics Under Whole-Body Vibration.* (Doctor of Philosophy), The University of Michigan.

Butler, B. P., & Alem, N. M. (1994). Apache Helicopter Seat Cushion Evaluation. *USAARL Report, No. 94-32*.

Butler, B. P., & Alem, N. M. (1997). Long-Duration Exposure Criteria for Head-Supported Mass. *USAARL Report, No. 97-34*.

Charles, L. E., Ma, C. C., Burchfiel, C. M., & Dong, R. G. (2018). Vibration and Ergonomic Exposures Associated With Musculoskeletal Disorders of the Shoulder and Neck. *Safety and Health at Work, 9*(2), 125-132. do**i:**https://doi.org/10.1016/j.shaw.2017.10.003

Dupuis, H., & Zerlett, G. (1986). *The Effects of Whole-Body Vibration* (1 ed.): Springer-Verlag Berlin Heidelberg.

Dupuis, H., & Zerlett, G. (1987). Whole-body vibration and disorders of the spine. *International Archives of Occupational and Environmental Health, 59*(4), 323-336. doi:10.1007/BF00405276

Griffin, M. J. (2004). Minimum health and safety requirements for workers exposed to hand-transmitted vibration and whole-body vibration in the European Union; a review.

Occupational and Environmental Medicine, 61(5), 387-397. doi:10.1136/oem.2002.006304

Hansson, T., Magnusson, M., & Broman, H. (1991). Back muscle fatigue and seated whole body vibrations: an experimental study in man. *Clinical Biomechanics, 6*(3), 173-178. doi:**https://doi.org/10.1016/0268-0033(91)90030-T**

ISO-2631. (1997). ISO 2631: Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration.

Kinsler, R., Khouri, R., Squire, C., Conti, M., & Wurzbach, J. (2018). Immobilization and Vibration Mitigation Systems: Test and Evaluation of Current and Developmental Products. *USAARL Report, No. 2018-13*.

Kittusamy, N. K., & Buchholz, B. (2004). Whole-body vibration and postural stress among operators of construction equipment: A literature review. *Journal of Safety Research, 35*(3), 255-261. doi:**https://doi.org/10.1016/j.jsr.2004.03.014**

Magnusson, M., Hansson, T., & Broman, H. (1988). Back muscle fatigue and whole body vibrations. *Orthop Trans, 12*, 598.

MIL-STD-810G. (2008). MIL-STD-810G. Test Method Standard for Environmental Engineering Considerations and Laboratory Tests.

MIL-STD-1472G. (2012). MIL-STD-1472G. Design Criteria Standard: Human Engineering.

Pope, M. H., Magnusson, M., & Wilder, D. G. (1998). Low Back Pain and Whole Body Vibration. *Clinical Orthopaedics and Related Research®, 354*, 241-248.

Pope, M. H., Wilder, D. G., & Donnermeyer, D. D. (1986). Muscle fatigue in static and vibrational seating environments. *AGARD Backache and Back Discomfort 10 p(SEE N 87-13932 05-52)*.

Rakheja, S., Dewangan, K. N., Dong, R. G., & Marcotte, P. (2020). Whole-body vibration biodynamics - a critical review: I. Experimental biodynamics. *International Journal of Vehicle Performance, 6*(1), 1-51. doi:10.1504/ijvp.2020.104493

Seidel, H. (1988). Myoelectric reactions to ultra-low frequency and low-frequency whole body vibration. *European Journal of Applied Physiology and Occupational Physiology, 57*(5), 558-562. doi:10.1007/BF00418462

Seroussi, R. E., Wilder, D. G., & Pope, M. H. (1989). Trunk muscle electromyography and whole body vibration. *Journal of biomechanics, 22*(3), 219-229.

White, G. H., Lange, K. O., & Coermann, R. R. (1962). The Effects of Simulated Buffeting on the Internal Pressure of Man. *Human Factors, 4*(5), 275-290. doi:10.1177/001872086200400504

U.S. Army Aeromedical Research Laboratory
Fort Rucker, Alabama

All of USAARL's public release and limited distribution technical reports are available for download from the Defense Technical Information Center.

https://discover.dtic.mil/results/?q=USAARL

Army Futures Command
U.S. Army Medical Research and Development Command